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RESEARCH ARTICLE

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Computing geographical access to services: The design of a client–server solution that incorporates multiple transport modes

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Abstract

This study describes the design and implementation of a web-based infrastructure built on open-source components to enable the computation of accessibility scores. It can be adapted to any form of service provision that is represented as geo-located points. The solution aims to extend previous attempts to measure and analyse geographical accessibility in a web-based environment. This design integrates a new approach for generating the variables required in calculating accessibility scores, while allowing the whole system to potentially remain as an open-source and open-data solution. The design allows accessibility scores to be computed using simultaneously both public and private transport modes, thus presenting a more accurate assessment than that obtained from standard single-mode solutions. The infrastructure is described through a consideration of each fundamental component, demonstrating how travel distances and alternative journeys are generated and applied to the accessibility model. Results produced by the solution enable the comparison of accessibility scores generated from alternative modes of transport and are illustrated using a case study to investigate access to sports facilities in Wales. This demonstrates how the system can be used to guide further investment and the future management of service infrastructure.

1 | INTRODUCTION

In Wales, as elsewhere, the national governing body of sport has, as one of its principle aims, the target of ensuring sufficient and equitable access to both sporting facilities and sporting opportunities. In order to achieve this goal, such organisations need to develop systems and tools that enable changes in service provision to be monitored, particularly in relation to the distribution of key demographic groups who traditionally have low participation rates in sport. Several previous studies have been concerned with developing spatial tools to investigate variations in access to sporting infrastructure. These have adopted a range of technical approaches, including those that measure distance or travel impedance to the nearest provider, or studies that adopt cumulative opportunities approaches to count the number of providers present within a given time or distance of potential customers (e.g., Cereijo et al., 2019; Karusisi, Thomas, Méline, & Chaix, 2013; Shen, Cheng, Huang, & Zeng, 2020; Shrestha, Kestens, Thomas, El Aarbaoui, & Chaix, 2019), whilst others implement more sophisticated methods based on gravity modelling approaches (e.g., Billaudeu et al., 2011; Bryant & Delamater, 2019; Martori, Apparicio, & Séguin, 2020).

Regardless of the methodology adopted, a common assumption is that all individuals can freely travel via means of private transport and so these studies typically do not consider variables such as the availability of car ownership, the percentage of people using public transport, or the percentage of population (or their age ranges) that are likely to make use of alternative types of sporting facilities. This indicates one of the key components required to measure accessibility more accurately and identifies several research questions, such as: How can these alternative modes of transport be implemented into an accessibility measurement model? What would be the best method to collect information on variables such as travel time and distance? In addition to these questions, other problems also need to be considered. Many of these organisations work across multiple locations and collaborate with one another, and some organisations are also lottery funded or have sparse resources/income. This identifies two additional problems. First, how can the system be kept at a low cost to those organisations and potential users with sparse resources and income? And second, how can the system allow users to collaborate and be accessible from off-site when required? Finally, one further concern is that the users of these systems may not come from a GIS background, which requires that the solution should be intuitive, easy to understand, and utilise simple forms of interaction. Within this article we aim to address each of these questions in turn by providing solutions to problems that will be familiar to many of those concerned with developing such systems.

This study aims to build upon existing research to develop a potentially more sophisticated approach by incorporating multiple modes of transport into accessibility measures, along with the development of a new web-based infrastructure solution to allow users to visualise and analyse the impacts of alternative configurations of sporting infrastructure via a browser interface. This infrastructure provides the necessary variables that are required to calculate the levels of accessibility with the chosen accessibility model. Alternative modes of transport are normally available to populations seeking access to facilities and so should be considered when evaluating how accessible facilities or services are when using each mode of transport (or indeed a combination of different modes of travel). As an example, those able to travel only via public transport using the fixed routes and timetable available will inevitably experience lower accessibility to potential service providers when compared to those who have use of a private car. Our aim, therefore, is to provide external governing bodies, who work alongside organisations that oversee the planning and maintaining of sporting infrastructures, tools to assist in measuring spatial patterns of accessibility for existing and projected levels of provision in relation to potential population demand arising from a range of alternative transport modes.

This article describes the design and implementation of a new client–server web-based solution to enable the calculation and visualisation of outputs from the application of advanced accessibility models that can provide information to help optimise the availability of public services. The process of collecting open data, along with the challenges faced with using selected open-source solutions, are also described. The design and input requirements of the system were defined after close consultation with its anticipated users. Potential users were involved from the outset, with surveys helping to specify the initial user requirements. Furthermore, the system described here has progressed through several design iterations, each informed by comments and feedback received from testers based at partner organisations using early prototypes, and we continue to work closely with them to further enhance system usability. User testing, analysis and feedback from such organisations is an essential component in the development process, and is understood to be vital in developing a solution that will be readily accepted and used by both sports organisations and other decision-makers who might seek to use it to apply to alternative point-based services that are of their concern.

The specific model used for accessibility measurement is based on the enhanced two-step floating catchment area (E2SFCA) model as described by Luo and Qi (2009), with further adaptations designed to allow sub-cohorts to travel via alternative transport modes as developed by Langford, Higgs, and Fry (2016). The solution[1] aims to utilise open-source online data resources and computational tools that are integrated into a web-based delivery environment. The proposed solution benefits from the advantage of being available via a web browser from any platform capable of accessing the internet, specifically a desktop PC, laptop, tablet, or mobile phone. The access from anywhere browser-based interface encourages collaboration between different groups or organisations that require data and resources to be shared. Furthermore, a client–server solution relieves users from the burden of acquiring, configuring, storing, and maintaining the required data on each machine that uses the shared resource. Building the system from free and open-source technologies is also of benefit to those organisations with sparse resources/income and permits easy customisation of the system without the need for expertise in systems development.

To our knowledge, the type of approach taken to calculate the multiple-mode floating catchment area accessibility measures proposed within this article has not been used before. The components described have been configured to interact with one another through the use of multiple programming languages that ultimately exploit and combine their capabilities to produce accessibility scores and provide a means to visually present these via a browser-based web mapping solution. Additionally, to our knowledge, this is the first time a multiple-mode accessibility tool of this precise nature has been implemented in a web-based environment that enables the accessibility calculation system to be reached from any platform that has internet access and that is permitted to use the data. A summary of previous approaches to measuring accessibility, including that of the E2SFCA technique, is presented in the next section, which also considers the potential to extend these models to exploit the capabilities of route planner application programming interfaces (APIs) that are increasingly available in free and open-source software (FOSS) development environments. In Section 3 the architecture of a software solution that links a number of open-source components using several key web-based computing technologies and their associated languages is outlined. Each component required within the full solution is described in turn, leading from the initial configuration of the model through to the output and presentation of final accessibility scores. Section 4 presents a case study applying the system to data relating to the provision of gymnastics facilities in Wales. These represent a service supply, while census-based populated-weighted centroids with appropriately selected demographic data model the potential service demand. The case study specifically demonstrates the assessment of accessibility to this service via two alternative modes of transport, namely private car and public bus.

In Section 5 the benefits of the adopted approach are outlined, discussing how it can be adapted for use within any application area concerned with analysing spatial variations in service provision. This infrastructure permits a new method of collecting the datasets needed for accessibility measurements within a distributed client–server architecture environment as an alternative to solutions based on a plug-in for GIS software such as QGIS (2020) or ArcGIS Desktop (Esri, 2020), as have been developed in previous studies (e.g., Langford et al., 2016). The client–server solution has several key benefits, such as easy maintenance of key network datasets, which can be quickly and efficiently updated from online resources, and the ability to provide a service to multiple machines and platforms without encountering potential synchronisation issues.

2 | BACKGROUND

2.1 | Previous approaches to modelling accessibility

The term *accessibility* is used to describe the ease with which a person or number of people from one location can reach another location of interest, typically in order to take advantage of a proffered service at that site (Wang, 2007). The concept of accessibility and how best to conceptualise and measure it has been a major topic of discussion within quantitative geography literature for several decades. Published studies cover an enormous variety of application areas, such as healthcare, employment opportunities, transport network improvement, and disaster aid (Bao & Deng, 2011; Barbieri & Jorm, 2019; Fransen, Neutens, De Maeyer, & Deruyter, 2015; Langford, Fry, & Higgs, 2012; Narboneta & Teknomo, 2013). This interest has led to the development of many alternative approaches to calculating accessibility. According to Wang (2007), these can be categorised into four types of methodological approach. The first, proximity measures, are perhaps the most simplistic, whereby accessibility is reported as the nearest available service supply site. The second, cumulative opportunity, views accessibility as the total number of service supply locations that fall within a specified distance or time of travel. The third set of approaches is based on geographical gravity models, as proposed by Hansen (1959). These are founded on Newton's law of gravity and measure the attraction and potential interaction between any two sites as a combination of their relative sizes mitigated by their geographical separation. The final category is time-space models which, according to Weber (2003), consider accessibility as a combination of opportunities intersecting with an individual's daily movements and routines. Traditional approaches to measuring accessibility in GIS studies tend to be based fundamentally on either density (*container*-based) or distance (*proximity*-based) techniques. The container-based approaches report a supply-to-demand ratio as found within a given administrative/catchment area, while the distance-based approaches compute either straight-line or network-based impedance as the travel distance or travel time to the point of provision.

2.2 | Two-step floating catchment area models

A relatively recent development in geographical accessibility literature has been the emergence of the so-called two-step floating catchment area (2SFCA) methodologies. The 2SFCA model is a type of gravity-based model, first proposed by Radke and Mu (2000) and later modified by Luo and Wang (2003). In step one it uses catchments constructed around service points to generate a supply-to-demand ratio using its estimated contained population count. The second step constructs a catchment around each demand centre and sums all contained supply-to-demand ratios to yield a final accessibility score. This method improves upon simple distance-based accessibility by considering the population competing for any given service supply point.

Since it was first developed there have been many implementations and modifications to 2SFCA. One of the most important of these is the enhanced method (E2SFCA) proposed by Luo and Qi (2009), which adds a distance–decay function to all network distances, thereby reducing the score the further away the demand is from the supply. This addresses otherwise unrealistic assumptions that each member of the population is willing to travel the same distance and ensures that the *attractiveness* of a service decays in proportion to its distance from the user. This model is expressed algebraically, thus:

Step 1

$$R_j = \frac{S_j}{\sum_{k\epsilon\,(d_{kj} \le d_0)}^{P_k \cdot W_{kj}}} \tag{1}$$

where R_j is the supply-to-demand ratio at supply location *j*. The supply volume, or how the facility is evaluated in terms of its supply quality (e.g., number of tennis courts, number of hospital beds, hours of opening, etc.) is represented by S_j. P_k is the population at location *k* that falls inside the catchment area of *j*. The catchment area is represented as $d_{kj} \leq d_0$, where d_{kj} is the cost (in distance or time) for supply location *j* to demand location *k*, with the maximum catchment threshold represented as d_0.

Step 2

$$A_k = \sum_{j \in (d_{kj} \leq d_0)} R_j . W_{kj} \tag{2}$$

The final E2SFCA accessibility score A_k assigned to location *k* is the sum total of all supply-to-demand ratios R_j that fall inside the catchment area of *k*. W_{kj} is a weighting between 0 and 1 that represents the effects of the distance–decay function adopted.

Whilst there have been many studies concerned with examining accessibility to a wide range of services using FCA approaches, relatively few have attempted to measure access to sporting facilities. One of the few examples, by Cutumisu and Spence (2012), applied E2SFCA to measure access to sports fields with a catchment size of 1,500 m for pedestrian access. The E2SFCA method was applied using ArcGIS and its Network Analyst extension but did not include multiple forms of transport. Another FCA-based study of access to sports facilities was conducted by Langford, Higgs, and Radcliffe (2018); again, this study implemented its solution in ArcGIS and used a bespoke plug-in tool to calculate E2FCA scores by leveraging the Network Analyst extension within the solution.

These examples both used proprietary software to calculate accessibility, which can present a cost burden on organisations with limited financial resources. Furthermore, both assume the exclusive use of a single mode of transport, which in reality is quite unlikely, and which may depend heavily on the specific sport under consideration and the particular age groups that make use of different types of recreational facilities (Office for National Statistics & Welsh Government, 2016–2017). The solution presented in this article improves upon these studies by allowing several alternative modes of transport to be included, simultaneous within the accessibility model. Thus, it offers an incremental improvement over previous studies, better evaluating current and projected levels of service provision using a realistic combination of available transport modes. Nevertheless, some potentially important limitations remain. A fully multi-modal solution allowing travellers to swap freely between any travel mode during the journey is not currently accommodated. The proposed solution allows some combinations of walking, cycling, and transport by public bus and train to be considered, but others—such as a journey that begins by car, then swaps to train, and is completed by city-bike—are not included. Other real-world factors affecting transport choices, such as potential capacity constraints and costs associated with parking at a train station, or the availability and additional cost of destination-point parking for car travellers, are likewise unaccounted for and so remain in the realm of future research.

2.3 | Multiple-mode accessibility within FCA models

Although various enhancements to E2SFCA have been proposed, Mao and Nekorchuk (2013) noted that most previous studies make the assumption that access to the service is achieved via a single transport mode, typically assumed to be private car. Because this assumption is questionable, they suggested an approach to accommodate alternative transport modes. This was achieved rather simplistically by applying different travel speeds along each network link according to transport mode. This has some value in mimicking the slower progress on public transport caused by frequent stops for passengers to board and alight, but remains unrealistic in terms of assuming that buses can use all the same routes and roads as a private car. These limitations have led to further developments of multiple-mode E2SFCA to better accommodate the nature of disparities between public and private travel.

The study by Ni, Liang, Lin, Wu, and Wang (2019) discusses the difference associated with each mode of transport that would most likely need to be considered, referring to this as ‘door-to-door’ journeys. Each journey is broken down into sections that include walking distances from the door to the mode of transport, and any transfers between transit systems that might occur within the journey. This highlights the use of different modes of transport and the potential impact it may have on overall accessibility scores. Applying data to evaluate health-care services, the Baidu Maps API (Baidu Maps, 2020) was used to generate an origin–destination (OD) matrix concerning potential service supply, and Microsoft Visual C++ and Esri ArcObjects used to implement the E2SFCA procedure. Ma et al. (2019) adopt a similar implementation, again using Baidu Maps to calculate travel data; however, they apply it to a different multi-modal computation referred to as a 3SFCA model that creates an additional step for each mode of transport required. All these examples provide implementations of E2SFCA in a multiple-mode form but require the user to register with an online service, which will incur usage costs; this contrasts with the solution outlined in Section 3 of this article. Additionally, none of these approaches were aimed towards the analysis of multiple-mode access to sporting infrastructure.

One of the more recent approaches to multiple-mode accessibility measurement is the model proposed by Langford et al. (2016) that modified the standard E2SFCA to accommodate any number of transport types. The E2SFCA step one computation becomes:

$$R_j = \frac{S_j}{\sum_{K\epsilon d_{kj},1 \le d_{0,1}} P_k,1 \cdot W_{kj} + \sum_{K\epsilon d_{kj},2 \le d_{0,2}} P_k,2 \cdot W_{kj} + \cdots + \sum_{K\epsilon d_{kj},n \le d_{0,n}} P_k,n \cdot W_{kj}} \tag{3}$$

where R_j is again the supply-to-demand ratio at supply point *j*. S_j is the service supply volume at location *j*. P_{kn} is the sum of the population at location *k* that is within the catchment area of *j* for the particular mode of transport selected. Catchment area is represented as $d_{kj,n} \le d_{0,n}$, where $d_{kj,n}$ is the cost in travel time or distance for travel mode of type *n* at supply location *j* and demand location *k*. The catchment threshold for travel mode *n* is $d_{0,n}$. The distance–decay function W_{kj} can also vary independently according to the mode of transport.

The second step of E2SFCA is applied to each transport mode, thereby creating a separate accessibility score, and is calculated as follows:

$$A_{k,n} = \sum_{j \in d_{kj,n} \le d_{0,n}} R_{j.} W_{kj} \tag{4}$$

where $A_{k,n}$ represents the accessibility score at location *k* for the *n*th mode of transport. This equation is looped through for each mode (car, bus, cycling, etc.), resulting in a separate score for each mode. These different scores may then be applied to graphs or maps to compare E2SFCA accessibility measures taking alternative modes of transport into consideration.

2.4 | Multiple-mode network distances

After evaluating some of the E2SFCA models and multiple-mode variants, it is evident that a key component in all is the generation of impedance, be this distance or time, between origins and destinations and within respective catchments based on either a straight-line or ideally network threshold distance. To enact a multiple-mode system requires a method to calculate the routes most likely to be used for a variety of transport modes. For example, a car has almost unlimited access to the road network and so will adopt a path that offers the shortest travel distance/time, whereas a bus or other similar modes of transport are limited to the routes that buses operate upon and may also have a maximum tolerated walking distance to connect to and from the designated stops. There have been many studies based around the use of route planners, the tools used for computing these pathways, each highlighting the various ways in which they can be applied or how their perceived limitations will affect the resulting routes and distances calculated.

Previously highlighted studies, such as those by Ni et al. (2019) and Ma et al. (2019), used Baidu Maps as the route planner within their system. However, many other route planners are available, each using different computing technologies and libraries, and these may be adopted as alternative solutions. Baidu Maps is similar in nature to Google Maps in using API calls to servers that are not maintained or controlled by the user. This has the potential advantage of eliminating the need for the user to update data and routes information, but almost all these services charge for their usage. Open-source route planners exist that require some initial set-up and data maintenance, but which do not then incur ongoing subscription fees. Studies such as Dornhofer, Bischof, and Krajnc (2014) have compared and evaluated alternative open-source route planners such as OpenTripPlanner (OTP, 2020), pgRouting (2020), and the Open Source Routing Machine (OSRM, 2020), noting their advantages and disadvantages and discussing how they can be deployed in such a system. An R package was recently created by Tsalamanis (2018) in which the OTP REST API is called upon using a CSV file OD matrix as the input, to produce distances and journey routes along with isochrone maps. This study further enhances this approach to a solution by embedding the OTP REST API into a fully web-based system that reads directly from a PostGIS spatial database, as detailed in the following section.

3 | METHODS

3.1 | Accessibility measurement and multiple-mode network distances

In this study the selected method for measuring accessibility is the multiple-mode variant of E2SFCA proposed by Langford et al. (2016). To supply this model with time/distance calculations, this algorithm is integrated with API calls to an open-source route planner that supplies the results associated with each mode of transport. This benefits from the inclusion of both public and private transport systems to present a potentially more sophisticated approach to measuring accessibility than those using cumulative opportunity or nearest facility methods. It also permits a comparison of accessibility calculated for each mode of transport, which can aid future decision-making processes aimed at addressing the equity of access for different population groups.

To operationalise a multiple-mode accessibility tool, a route planner is needed to collect and process journey information between origin and destination locations. This information will report different road network distances and times according to each mode of transport used, whether it be public bus service, private car, private bicycle, walking, and so on. There are many open-source route planners that could be deployed for the journey calculations required for the accessibility models. Again, studies such as Dornhofer et al. (2014) have compared the functionality of alternative route planners such as OTP, OSRM, and pgRouting. It was clear from these studies that OTP would be most suitable for a multiple-mode accessibility model because it is capable of taking into consideration bus timetabling and other similar information for public transport routes. The OSRM product did not contain such timetable information, although it was capable of supporting route relations to public transport.

Based on this understanding, OTP was selected for use in this study. OTP is a free and open-source Java-based solution that can readily be integrated into a web-based environment. Previous studies have used OTP to generate journeys for designing route paths, for providing aid in disasters, and for general trip generation (e.g., El-Geneidy et al., 2016; Mirri, Prandi, Roccetti, & Salomoni, 2017; Narboneta & Teknomo, 2013; Prandi et al., 2019). However, to our knowledge, no study to date has used OTP to generate multiple-mode E2SFCA scores. OTP promotes itself as a multi-modal journey planner that identifies itineraries based on user inputs and which is designed to work on multiple platforms including Windows, OSX, Linux, or indeed any device with an operating system capable of running a Java virtual machine. When OTP is operating as a server, it can be continuously queried via its REST API, and in response returns journey information in JSON format. This allows OTP to be used as a back-end tool to generate journeys and their associated distance and time data, which can then be incorporated into the E2SFCA accessibility model. The primary aim of using this tool in the present study is to utilise these capabilities to keep the proposed solution within a fully online environment.

3.2 | Data and data storage

To function effectively and obtain accurate accessibility results, data points relating to service supply and demand locations must be stored in a manner that affords easy access over the internet or a local area network. There are several open-source databases with geospatial extensions that could be used within the solution, however we elected to use a PostgreSQL database with PostGIS extension to store all such datasets. This is due to its extensive spatial functionality, as well as its close integration with many open-source GIS tools. Specifically, in this case study, demand population is modelled using population-weighted centroids of UK Census Output Areas, together with associated demographic data. Service supply is modelled using the point locations of gymnastics clubs, along with various service capacity and quality indicators. These point datasets are used to generate OD matrices that drive the accessibility modelling process.

OTP generates a topological graph consisting of a road network and structured transit information formatted as a General Transit Feed Specification (GTFS) file. This graph is used to create a public transport network, snapping key locations such as bus, tram, and train stops onto the road network using supplied coordinates. GTFS data also contain route information specifying how a bus or train will travel from one stop to another, thereby linking all required bus stops for any given route. Transit route and time data were downloaded from traveline data (2019). This download is supplied in TransXChange format, an XML-based data standard, and was converted into GTFS format using converter software. This approach does, however, present a problem in creating a smooth transition each time transit data are updated on the OTP server. Ideally, the user would collect the data in GTFS format initially and place them within the data repository for building the network graph. However, data were derived from traveline data during this study because these are continuously updated on a daily basis and so offer the most recent routes and times for each mode of public transport used. OTP uses OpenStreetMap (OSM, 2020) as its underlying road network, to which the GTFS data are then connected. Due to its structure, OSM is the only network source that OTP can use for the road network. OTP documentation suggests that OSM data be downloaded from Geofabrik (2019). Geofabrik provides free data extracts of OSM, which is open data including roads, trails, railway stations, footpaths, and so on. By using this method of collecting OSM data, the user can easily select their desired geographic area before constructing the graph used by OTP. Figure 1 represents the data stored in the graph on the OTP server, with gymnastics facilities used as an example of a service provision that is stored in the Postgres spatial database.

All data used in this project are open data; however, maintaining a system that consists of public transport information can potentially prove difficult due to frequent updates to public service routes and timetables. Thus, a method needs to be implemented to allow the system to collect and update such data frequently, and ideally in a fully automatic manner, from within the web-based environment.

3.3 | System design

The system's infrastructure and processes are illustrated in Figure 2. The structure consists of four primary components, based on a combination of critical web technologies that include:

- HTML/CSS for browser interface development.
- JavaScript coding for client-side data processing and analysis.

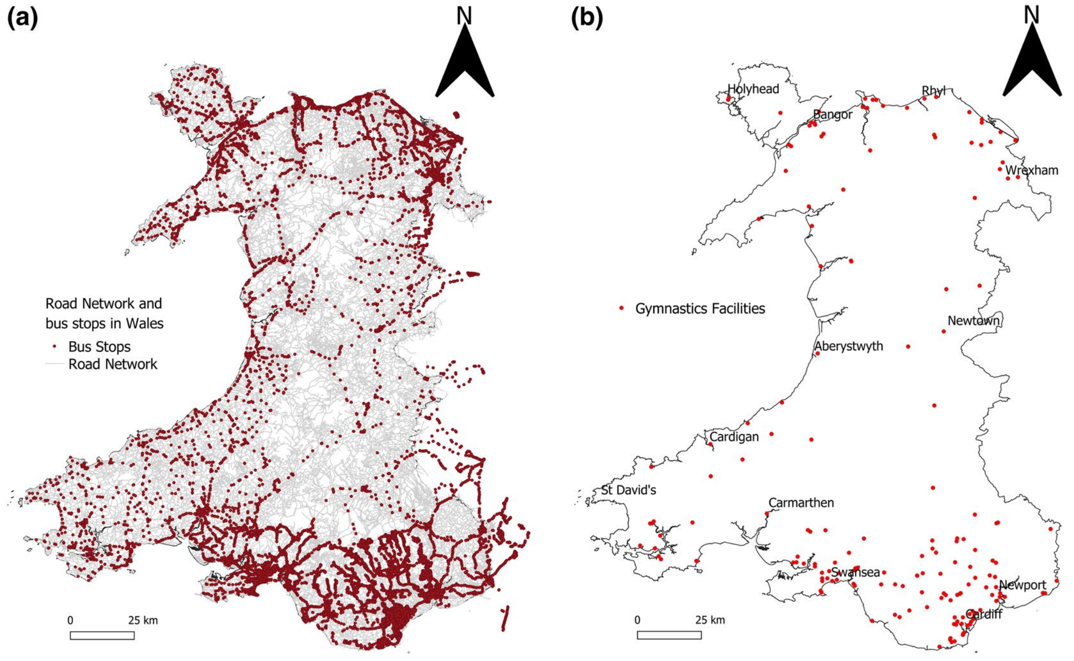

FIGURE 1 (a) Road network based on OSM at Geofabrik (2019) with bus stops and routes provided by traveline data (2019); and (b) Welsh Gymnastics facility locations

- PHP coding for server-side data processing and analysis.
- PostgreSQL/PostGIS for supply and demand points spatial data storage, OD matrix storage, and to support the E2SFCA computations.
- OpenTripPlanner for network journey tracking via both public and private transport modes.
- REST, JSON, and other web services for facilitating communication and data flow between the various servers and clients present within the infrastructure.
- Leaflet/OpenLayers JavaScript library to provide data visualisation and mapping support.

The first main component (identified as item **a** in Figure 2) is the web-based interface through which users interact with the system. The user may view the web application via their preferred web browser to interact with the web service containing each of the core PHP scripts that perform the tasks needed to gather information prior to performing multiple-mode E2SFCA calculations. Each page of the web application allows the user to select the desired data inputs needed to drive the accessibility calculation, and to specify any modelling parameters before initiating the analysis. An example of the parameters that may be set here is the choice of transport services (car, bus, bicycle, walking), and the capacity/quality measurements that are associated with the supply points (e.g., total weekly opening hours, number of gymnastics coaches, number of sports activities supported, etc.). Figure 3 shows two of the input pages presented to the user that allow them to select whether to include journey distances and journey times in the output, and to set up key modelling parameters and inputs for the E2SFCA calculation itself. In Figure 3 the left panel shows the simple interaction style for system users, who need only click on buttons in the order that they are presented as each stage of the analysis is complete. The panel on the right illustrates the sort of inputs that a user can submit as parameters to control the precise nature of the E2SFCA calculation to be undertaken. Parameters presented in each form are fixed in terms of their data types (e.g., automatically selecting geometry fields) or are tables that are collected from specific schemas in the database to allow users to set up the analysis without selecting any potentially erroneous choices.

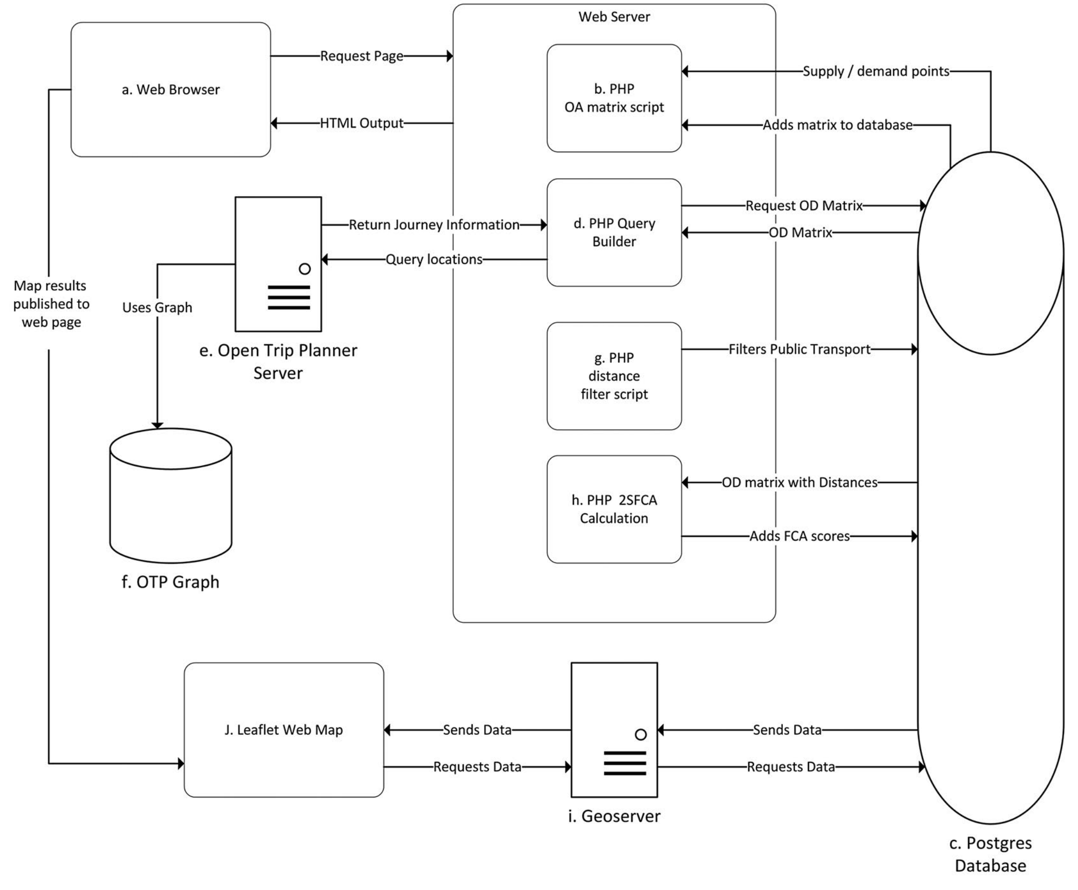

FIGURE 2 The infrastructure of the free open-source web-based accessibility calculation solution

The user is also asked to specify the maximum tolerated travel limit, specified as either a time or a distance, which is a key requirement of E2SFCA calculations. Another parameter used in the calculation is the distance–decay function (e.g., none, linear, Gaussian, etc.), which can be set by the user according to their preferences. The interface is designed to limit the user's selections where appropriate, such as by only listing those tables in the spatial database that contain a point geometry when seeking confirmation of supply and demand locations. The inputs to all other parameters are similarly validated to avoid erroneous calculations wherever possible.

PHP scripts stored on the web server are in constant contact with the Postgres/PostGIS service (identified as item **c** in Figure 2), which supplies and manages the supply and demand point datasets. It also plays a crucial role in storing intermediate results in hidden tables as the accessibility computations progress. Datasets for supply-side services contain sports facilities in this instance but they could store any supply-side service of interest, such as hospitals, banks, schools, pharmacies, and so on. The demand points are generally population-weighted centroids of a geographical area classification. Both sets of tables must contain a minimum of three columns for the purpose of calculation. The first is a primary key ID used to uniquely identify and track each location and associate it with each unique possible journey that is generated later by the OTP system. Second, a geometry field stores the point's location in WGS84 latitude/longitude coordinates. Finally, a service capacity (or demand volume) field is associated with each service supply point (or demand point). If no obvious measure of capacity is available for a

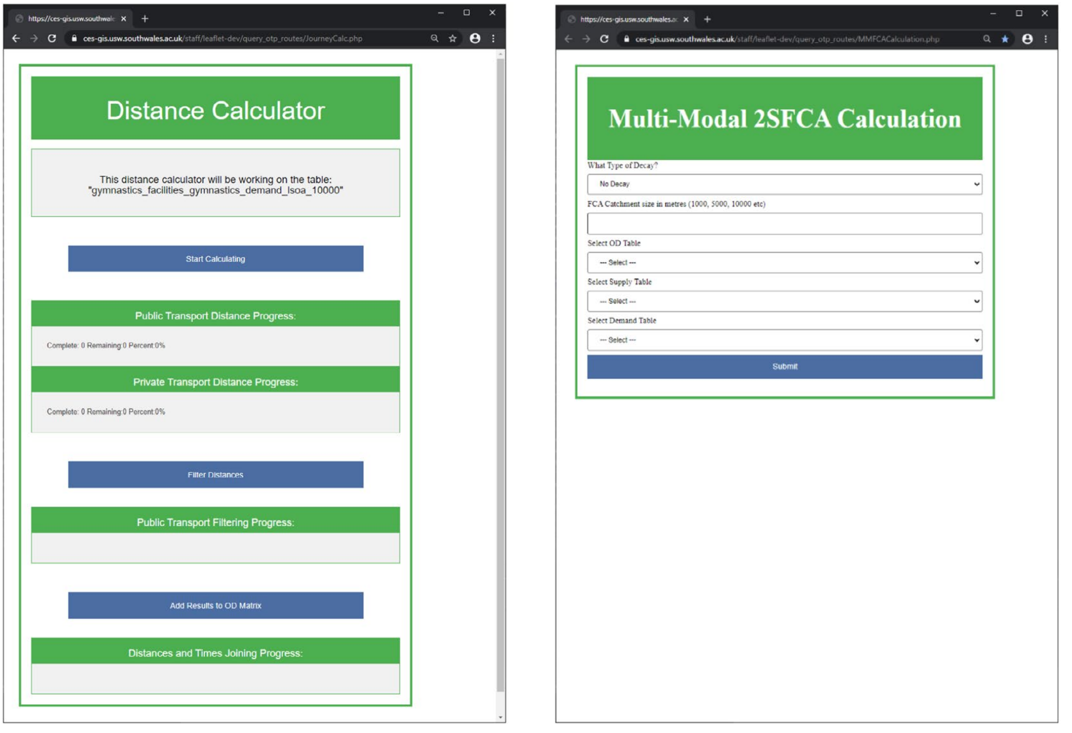

FIGURE 3 The web interface through which users input the desired modelling parameters. Left: The journey calculation input, public transport filtering, and combine to matrix options. Right: Key multi-modal E2SFCA calculation parameters

given service, these can be populated with a value of 1, and the E2SFCA scores will then return a score relating to the number of sites per population.

The task of the first PHP script (represented as **b** in Figure 2) is to contact the Postgres server and instruct it to create a first-pass OD matrix. This contains each possible combination of supply-point location and demand-point location according to the defined travel threshold limit and assuming straight-line travel. Using the parameters from the web application (a) the user can submit the variables from the web page and post them to the PHP script (b). This generates a spatial query for the Postgres database (c), which then takes advantage of the R-Tree indexing capabilities of PostGIS to very rapidly generate a table of all possible journey start and end points needed for the E2SFCA computation. Of course, the actual network distances between these points are always longer than their straight-line distances, so the OD matrix represents at this stage the absolute maximum set of supply–demand pairs that may be required for the E2SFCA calculation. Many of these cases may later be discarded from consideration when their network distance separation is found to exceed the E2SFCA threshold limit specified by the user when configuring the model.

The second PHP script on the web server (item **d** in Figure 2) retrieves the first-pass OD matrix stored on the Postgres server and prepares each item to be structured into a string. This string, once created, is passed as a URL to the OTP server, and it contains the coordinates of the origin and destination points. This URL string is used to query the OTP service (e), using its RESTful API to retrieve information from OTP. OTP typically responds by generating several different journeys that are possible for each OD combination. The journeys returned are based on the parameters added to the URL string to indicate items such as the mode of transport (car, bus, walking, cycling, etc.) and the maximum total walking distance tolerated within the return journey. Depending on the mode of transport selected, some queries will return just a single journey—the shortest possible path—whereas others return multiple possible routes and journeys based on the timetabling of buses, trains, and so on.

OTP uses its stored graph to generate all possible journeys between the specified origin and destination points. The graph (f) houses the two components needed to generate the routes and distances, the first being the road network sourced from OSM (Geofabrik, 2019) and the second being the GTFS file used to gather transit routes and times. Once all journeys have been calculated via the graph, OTP returns this information as the travel time, the network distance, the details of any transfers, the total walking distance, and so forth, back to the controlling PHP script on the web server. This information is then processed to extract network travel distance or time, and is used to update the currently stored OD matrix associated with each mode of transport. The OD matrix with the updated information on each journey is used to create new tables for each mode of transport, which are then fed into the calculation of the accessibility scores.

The OTP server typically returns several different journeys for certain modes of transport, such as public transit. This is due to the number of different routes that may be available and the routing and timetables of the transport. This causes potential conflicts due to there being more than one network distance for the trip. The purpose of PHP script (g) is to resolve such conflicts by filtering journeys to select either the fastest time solution or the shortest distance solution from amongst those presented, according to the user's preference. Not all transport types are passed through this script, as some will produce only a single distance or time reported back through the JSON response.

Once OD matrix generation is completed, with all desired modes of transport having their times and distances added, the multiple-mode accessibility scores are computed using PHP script (h). This PHP script generates a series of SQL queries directed again to the Postgres database server. Now, ignoring any supply–demand combinations with a reported network distance/time exceeding the specified floating catchment size, the first step of E2SFCA is computed independently for each transport mode selected. The availability scores, R_j, are written back into the tables that hold supply point locations. A second series of SQL queries is then created associated with step two of the ESFCA calculation, which ensures that these R_j scores are totalled as they relate to each demand location (i.e., fall within the catchment of that demand). These results are written back into the demand location table. As previously stated, the algorithm generates a separate service accessibility score relating to each transport mode at each demand location.

With the analysis complete, these tables can be made available to software such as QGIS to read directly from the Postgres database. However, to further enhance the user experience, they can also be accessed either directly through a PHP script, or more flexibly through a GeoServer instance, to provide information to client-side JavaScript which then leverages the mapping functionality of the Leaflet library (or alternatively, OpenLayers) to provide instant mapping of these scores within the user's browser (as seen in item **j** of Figure 2).

4 | CASE STUDY: MEASURING MULTIPLE-MODE ACCESSIBILITY TO SPORTING FACILITIES

To test the functionality of the developed system, appropriate supply and demand points are required. This study used a dataset of facilities supplied by one of the national sporting organisations in Wales (Welsh Gymnastics) to serve as supply locations. These are used alongside populated UK Census Lower Super Output Area (LSOA) centroids representing demand centres (Figure 1). Currently all servers, web services, and computing infrastructure (PHP processor, Java Virtual Machine, and so on) required by the model have been installed and configured, and test data as previously described have been assembled. Data were obtained from traveline (traveline data, 2019) to create the GTFS file, and OSM files needed for the OTP server are currently manually downloaded, and subsequently refreshed whenever timetables are significantly updated. Ideally, in future the downloading and updating of all data resources used for the OTP graph and network dataset will be automated, relieving this maintenance burden from the data analyst, and allowing them to focus on running accessibility calculations as required.

Results illustrate the expected outcome in a comparison of access to gymnastics facilities via public-only and private-only transport modes. The former, with longer journey times and more restricted routeways, led to lower scores than those based on private car travel. By creating separate estimates of accessibility according to transport mode, these maps reveal interesting spatial patterns that would be useful to the governing organisation in planning their future provision of facilities. Figure 4 shows the patterns produced by the original E2SFCA model proposed by Luo and Qi (2009) when generating road network distances via a single transport mode. Both public network distances and private network distances were used to create the two separate maps when these methods of travel were not competing. Neither of these results take into consideration the multiple forms of transport that would be available to the population.

Using network distances generated by querying OTP and applying these in the multiple-mode model proposed by Langford et al. (2016), it was possible to integrate both public and private transport simultaneously in a single system that uses the same OSM road network for both modes of transport. Figure 5 shows the results produced by the infrastructure for each populated weighted centroid when the demand population at each centroid is split using a 50:50 ratio between public and private transport. Values reported by each geographical polygon represent the accessibility score assigned to that LSOA. This score can be interpreted as the share that each individual resident at a given demand location has of the total supply-side capacity. They are a supply-to-demand ratio which, in this instance, reports the number of gymnastic training facilities available per 1,000 persons. Figure 5 illustrates the resulting difference in scores generated between the two transport modes, and how much share of the services is available to each cohort. A 50:50 split between bus and car travel is used here simply to illustrate the principle, but in future a more realistic estimate of actual transport mode usage could be generated that takes into account factors likely to influence this ratio, such as the age range of users, the local household availability of private cars, and so on. The solution provided by the infrastructure illustrates its potential to model a modal

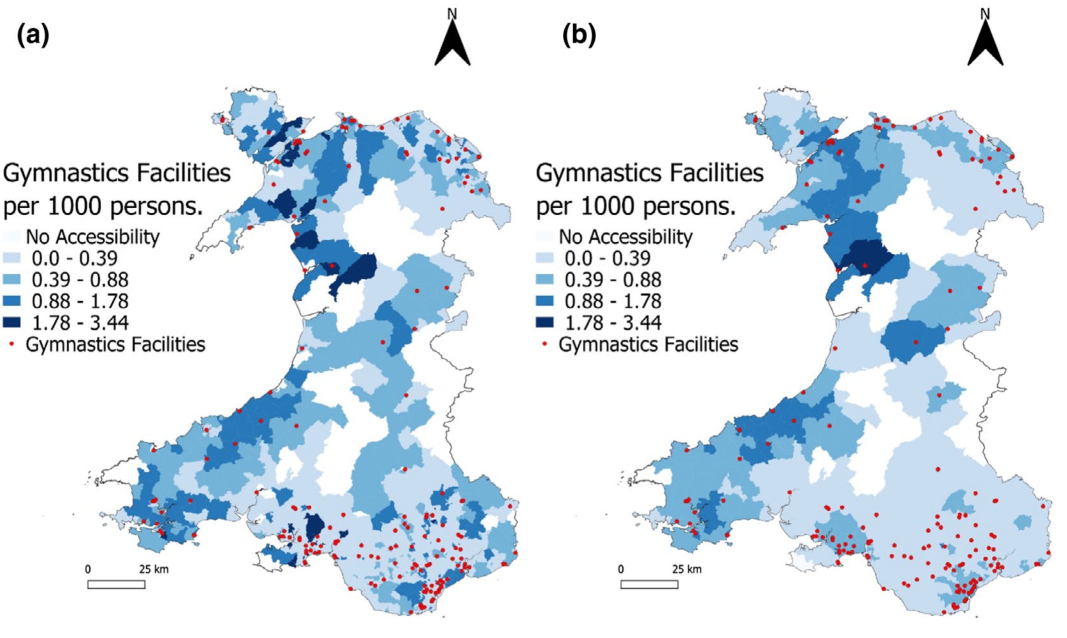

FIGURE 4 FCA scores for access to gymnastics facilities based on separate E2SFCA instances: (a) Public transport only with 45-min catchment and maximum 400 m walking distance to bus stops; and (b) Private transport only with 45-min catchment

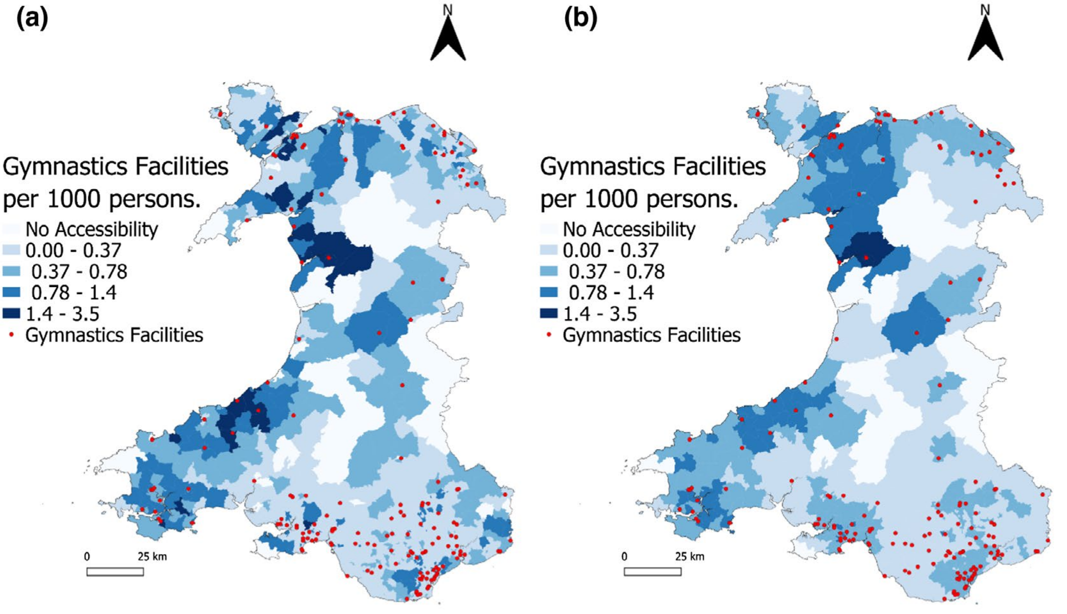

FIGURE 5 FCA scores for access to gymnastics facilities based on a multi-modal E2SFCA calculation, based on 50:50 split of the population at each demand centre using public and private transport: (a) Public transport with 45-min catchment and maximum 400 m walking distance to bus stops; and (b) Private transport with 45-min catchment

split, which could later be based on actual utilisation/behavioural patterns and survey information should these become available.

The outputs also demonstrate how these solutions can provide support over web-based environments with a fully interactive map for visual analysis of the outcomes. The web-based environment allows the system to be installed and maintained on just one machine rather than being replicated over each machine required to use such a system when sharing and collaborating with other organisations. Figure 6 shows a typical output presented in a web browser that provides interactivity through use of the Leaflet web mapping API. The user can pan and zoom freely around this map to study a particular area of interest, query the underlying data values via a popup window, and control which layers are to be displayed using a simple selection control mechanism.

5 | DISCUSSION AND CONCLUSIONS

The methods applied within this article extend previous approaches to measuring accessibility in several ways. Firstly, they provide a more detailed analysis of accessibility to sports facilities than those described in previously published studies (Cereijo et al., 2019; Karusisi et al., 2013; Shen et al., 2020; Shrestha et al., 2019). Rather than simple metrics such as nearest facility or cumulative opportunity, we compute E2SFCA scores. These provide better insight into accessibility by taking into consideration both the supply and demand for services within the local area. Furthermore, multiple transport modes are incorporated into the model, by adopting the algorithm developed by Langford et al. (2016). Multiple-mode access is measured using a web-based platform which avoids any reliance on proprietary software and licenced APIs such as those provided by Google Maps or Baidu Maps. This approach also maintains a consistent shared road network that can be used by both public and private access evaluations rather than maintaining different road network datasets for each mode of transport. It allows multiple modes of transport to be included and has the potential for customising the ratios and variables applied

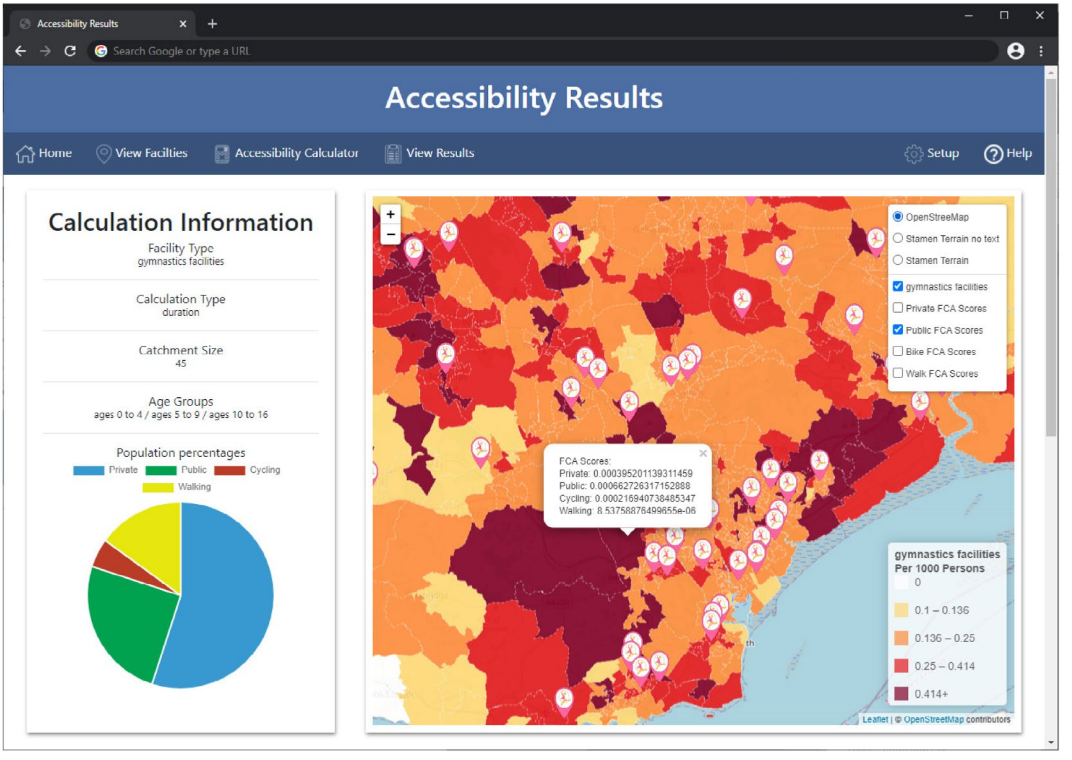

FIGURE 6 Example of output presented in a web browser with interactivity using the Leaflet web mapping API

within each model through an open-source solution. The outputs can aid decision-making for those organisations charged with measuring access to current and projected levels of provision; for example, the multiple-mode approach supports the ability to focus on those population cohorts less likely to own a car, or those age groups more likely to use alternative modes of transport to access (sports) facilities.

Secondly, results based on a facilities dataset provided in this instance by a national sporting body in Wales have shown how multiple modes of transport can provide a more complete assessment of accessibility that permits comparisons of scores derived from alternative modes of transport. In doing so, this goes beyond previous studies of access to sporting facilities such as that of Cutumisu and Spence (2012), which focused on pedestrian access only, or that conducted by Bryant and Delamater (2019), where road networks were used as a distance-based metric which could be applied to private transport or walking but which did not include variables such as time travelled or public transit timetabling. Furthermore, whilst developed in the context of access to sporting infrastructure, this same system is easily applied to an assessment of accessibility to a wide range of services, or can be easily adapted to the needs of different types of organisations.

Thirdly, although the system as currently developed utilises OTP as a core component of the modelling process, this route planner could be replaced by any similar tool that provides the required modes of transport that the user can then include in their analysis. OTP proves a beneficial solution to multi-modal approaches within accessibility measurements, including more advanced E2SFCA used within this study. The graph within OTP can be updated easily and in just one location using open data, freeing the user from subscriptions or limited function calls. However, alternative route planners such as Google Maps or Baidu Maps could be used in place of OTP using the JSON data that can be sent to or extracted from them even with subscription, in order to remove the need to maintain and update routes and transit stops. Both Ni et al. (2019) and Ma et al. (2019) have shown how Baidu Maps can be applied to a form of infrastructure and can be used to compute a multi-modal 2SFCA model.

To improve this model further, future research could involve implementing additional combinations of multiple modes of transport into a particular journey. One of the current examples available is the transit and bike option, which allows the combination of walking, bus, and bike. Additional options, such as car and bike, could be added also, for example to model situations where a traveller would park their car on the outskirts of a city and switch to a rental bike to travel further into the city. Other functionality that would require multiple transport modes to be added to car journeys could address issues relating to parking and private transport. Currently, car-based routes used within the project do not include a door-to-door approach and assume the user travels to the service point directly. In reality, travellers must use a car park close to the target facility and then embark on a walking leg to complete the journey.

Fourthly, one of the key strengths of this approach is the adaptability and potential customisation of the open-source infrastructure. Thus, for example, the measurements of accessibility used in this study (based on E2SFCA approaches) are easily replaced by other accessibility approaches that require distances or times provided by a route planner. This could include both the nearest facility and cumulative opportunity methods, each providing a more simplistic alternative of accessibility measurement, but which may nevertheless on occasions be a preferred option. Currently, the system requires the need for a specialist to adapt the variables into the equations within the server PHP scripts. Once these equations are added, they could then be selected from a dropdown box or other form of web selection interface. Other customisations may focus on the output itself as the open-source web mapping library, Leaflet, has the ability to create new or use existing plug-ins to aid in visually analysing the data. Although this solution was constructed using only open-source components, primarily to keep it licence free and low cost, it would be interesting in future work to make direct comparisons of the cost effectiveness, functionality, and other additional variables that may affect the decision to use either an open-source focused solution or alternative propriety software. This would most likely involve the creation of a plug-in similar in nature to that developed by Cutumisu and Spence (2012), or Langford et al. (2018), but which was implemented to include the integration of public transport data.

The method of collecting open data described in this article will ideally become an automated (or semi-automated) process in future, with minimal interaction and processes required to obtain and update the data. This data includes both the OSM data, which are downloaded from sites such as Geofabrik and placed in the graph repository for constructing the OTP graph later, along with the GTFS data required to allow the querying of public transport journeys and routes. Ideally, the user would download the updated GTFS data and place them within the graph repository, rather than downloading the data, converting, and then placing them within the folder. The data used within the duration of the study were updated daily by traveline data, making for a suitable source of data even with the additional process of converting the data.

The solution described in this article has been specifically developed to enhance the visualisation and understanding of accessibility to any service represented by point locations on a map. The solution is also designed to work in a web-based framework to aid organisations that collaborate and share resources, or for those organisations that require accessibility measurements to be calculated from anywhere with access to the web. The system developed uses a variety of free open-source and open-data tools as part of a low-cost solution that keeps data accessible and enables easy maintenance of an infrastructure that permits accessibility to be measured and visualised under a range of scenarios. This infrastructure is distinctive in that it has been built around open-source solutions that may be exchanged for alternative tools/methods in future, depending on user preferences.

Whilst the infrastructure developed and described here has addressed key research questions and problems posed in Section 1, it should be noted that overcoming these has not been a trivial exercise. To enable alternative transport modes to be implemented into a 2SFCA accessibility model required integration with a route planner. The solution adopted (OTP) necessitated code development in multiple programming languages to enable the issuing of specific journey itinerary requests and to then manage and interpret the response and extract information needed for 2SFCA. Throughout the process, multiple data items needed to be stored, retrieved, and spatially queried, which led to the adoption of the PostgreSQL database as a central repository, linking together all the key systems involved. In addition to data storage tasks, critical geospatial operations were accomplished in PostgreSQL too by using the PostGIS extension, and in particular its spatial-indexing capabilities, which allowed a fast and efficient algorithm to lie at the core of the solution. Furthermore, interaction between the central database and web server to accomplish the display of outputs required code development in still more languages and for complex SQL string building. All key components of the system remain open source, thereby achieving the objective of developing a low-cost solution. Both the input of modelling parameters, and the output of results, has been achieved via a standard browser interface, thereby meeting the objective of maintaining access to the tool across multiple platforms and physical sites and promoting easy collaboration between remote users. The direct output of results in the form of maps was facilitated by integrating code with the web mapping library Leaflet.

Finally, the ability to keep the system as a web-based tool has been shown to benefit a collaborative approach to measuring accessibility in organisations that require the tool to be accessed from any machine with appropriate permission rights. The web-based solution provides ease of mind to users, who are likely to come from a data analyst background with responsibilities to maintain and update such systems. The system only requires updating and maintenance on one machine, which can be done by a specialist, in addition to providing additional functionalities that could be added in the future. This could include the automatic updating of times and routes in the route planner, which could be implemented every time the user requires the analysis or each time the timetables and routes are updated to provide accessibility scores based on the most recent changes to the public transport network. A further enhancement could revolve around a ‘what-if’ scenario function, where the user is able to interactively add or remove facilities on the map and the system automatically updates accessibility scores based on these new facility locations. The user will then be able to view accessibility scores in real time in a web-based environment, which will aid decision-making within organisations that share sparse resources. Plans are in place to continue to develop these features and to implement further interface design improvements by working closely with those organisations that will likely be using such systems, responding to usability testing and other feedback that is received from them. These avenues of extended development will be explored as part of our future research plans.

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ENDNOTE

[1] The solution will be offered in due course as an open-source tool with all code posted on GitHub, but its code is currently withheld as the work contributes towards the potential award of a PhD.

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